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***published in***
Sustainability
2013

***DOI (link to publisher)***
10.3390/su5031011

***document version***
Publisher's PDF, also known as Version of record

*Sustainability* **2013**, *5*, 1011-1035; doi:10.3390/su5031011

OPEN ACCESS

*sustainability*

**ISSN 2071-1050**

www.mdpi.com/journal/sustainability

*Article*

# The Climate Adaptation Frontier

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*Received: 5 November 2012; in revised form: 7 January 2013 / Accepted: 6 February 2013 / Published: 6 March 2013*

**Abstract:** Climate adaptation has emerged as a mainstream risk management strategy for assisting in maintaining socio-ecological systems within the boundaries of a safe operating space. Yet, there are limits to the ability of systems to adapt. Here, we introduce the concept of an "adaptation frontier", which is defined as a socio-ecological system's transitional adaptive operating space between safe and unsafe domains. A number of driving forces are responsible for determining the sustainability of systems on the frontier. These include path dependence, adaptation/development deficits, values conflicts and discounting of future loss and damage. The cumulative implications of these driving forces are highly uncertain. Nevertheless, the fact that a broad range of systems already persist at the edge of their frontiers suggests a high likelihood that some limits will eventually be exceeded. The resulting system transformation is likely to manifest as anticipatory modification of management objectives or loss and damage. These outcomes vary significantly with respect to their ethical implications. Successful navigation of the adaptation frontier will necessitate new paradigms of risk governance to elicit knowledge that encourages reflexive reevaluation of societal values that enable or constrain sustainability.

**Keywords:** climate change; adaptation; limits; sustainability; adaptive capacity; resilience

## 1. Introduction

The pursuit of climate adaptation has expanded rapidly in recent years, due to increasing awareness of its potential value with respect to reducing societal and ecological vulnerability to current climate variability, while managing the risks posed by future climate change [1–4]. Whereas once adaptation was viewed as a "taboo" topic that was largely excluded from policy debates regarding climate risk management [4,5], adaptation is now being institutionalized at a range of geopolitical scales. Adaptation, and particularly adaptation finance, has become a major subject of debate within international negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). Various funding mechanisms have been developed to support adaptation in developing nations [3,6,7], although concerns have been raised regarding potential declines in financial capital supporting those mechanisms [8]. National governments of developed nations have also initiated strategic thinking regarding adaptation, as represented by the United Kingdom's Climate Change Act, Australia's National Climate Change Adaptation Strategy and the Obama Administration's Executive Order 13,514, which requires US federal agencies to assess and manage the risks posed by climate change to agency missions. Such top-down approaches to adaptation are complemented by a broad range of bottom-up efforts represented by local/municipal and state/district adaptation planning [9–14].

Much of the current policy focuses on adaptation; however, it is directed toward considerations of whether or not adaptation options are justified given uncertainty about the future. For example, the adaptation literature frequently advocates the pursuit of "win-win", "no regrets" or "robust" adaptation policies and measures that can be justified independent of climate change or that yield benefits over a wide range of plausible climate futures [2,15–22]. Such policies are politically expedient, as they avoid trade-offs that might otherwise constrain adaptation planning and implementation. The preoccupation with whether or not adaptation options are justified, however, has marginalized the more paramount consideration of what adaptation efforts will ultimately be needed to achieve societal objectives and whether or not those efforts can and will, in fact, be implemented. For example, "win-win" and "no regrets" adaptation policies and measures designed to manage current vulnerability, and modest magnitudes of climate change are unlikely to be adequate to achieve adaptation objectives over the long-term, particularly if climate change continues unabated [23–25]. The limits of such options to achieve adaptation objectives will eventually be reached, resulting in loss and damage [26].

There is, therefore, an "adaptation frontier", which remains largely unexplored for many valued socio-ecological systems. Should significant progress be made in coming decades with respect to greenhouse gas mitigation efforts, climate change may be restricted to rates and magnitudes to which many systems can cope or adapt with minor or modest incremental adjustments. However, in the absence of such success, systems will find themselves in uncharted territory and subjected to adverse and potentially irreversible consequences that will leave future generations with an Earth that is less rich than today, at least in an ecological sense. While international greenhouse gas mitigation efforts are now focused on keeping the change in global mean temperature below 2 °C above pre-industrial levels, at present, there is little evidence that such a threshold will be met [27,28]. In fact, some are already suggesting that socio-ecological systems will have to adapt to much higher magnitudes of climate change [23–25]. Such adaptation will also transpire in tandem with and in response to other types of biophysical and socioeconomic change that put additional pressure on systems of interest.

The key questions that therefore arise are: what is the likelihood that a given system of interest will reach the adaptation frontier, and if it does so, what will transpire once there?

Here, this concept of an adaptation frontier is introduced and linked to other concepts in sustainability science. This is followed by the identification of critical driving forces that define the frontiers of adaptation and discussion of the prospects for substantive changes in the trajectories of socio-ecological systems that would allow those systems to avoid falling off the frontier's edge. Subsequently, the paper explores the possible outcomes for systems that find themselves within frontier territory and how they might find their way back to more sustainable regions. The paper concludes with some discussion of the implications of the adaptation frontier for how adaptation researchers and practitioners frame the concept of adaptation and the extent to which more optimistic or pessimistic socio-ecological futures will prevail.

## 2. Defining the Frontier

The concept of an adaptation frontier is shaped by the integration of two emerging literatures in sustainability science. First, Rockström *et al.* [29,30] have introduced the concept of a "safe operating space" for human society, which is defined by multiple biophysical "boundaries" in the Earth system that span climate change, biogeochemical cycles, land and water use and chemical pollution. Pushing the Earth system beyond these boundaries jeopardizes the sustainability of valued ecosystem goods and services that support human enterprise. While analogous to "thresholds" or "tipping points", Rockström *et al.* emphasize that these various boundaries interact. As one boundary is exceeded, the likelihood of the exceedance of other boundaries and unsustainable outcomes increases. Therefore, understanding of what constitutes a safe or unsafe space for elements within the Earth system is shaped by multiple driving forces rather than singular thresholds. When adaptation is viewed through this lens, attention is focused not simply on whether it provides benefits, but whether it ultimately enables the societal values and management objectives to be sustained.

Rockström *et al.*'s planetary boundaries, however, focus on the biophysical elements of the Earth system. Human agency is acknowledged as an underlying factor influencing the risk of exceeding boundaries, but the role of human agency in responding to the resulting consequences is neglected. Granted, the implications of exceeding biophysical boundaries for humans are difficult to interpret in the absence of knowledge regarding the implications of that exceedance for societal objectives. When pressured by climatic and non-climatic stresses that overwhelm systems' existing coping mechanisms, adaptation policies and measures can be implemented to help sustain a system. Such adaptation can ultimately expand the coping range, adjust the system to maintain current objectives or transform the system. This leads, however, to another growing literature, which explores the limits with respect to the rate and magnitude of change to which socio-ecological systems can adapt [2]. Rather than such limits being defined by biophysical thresholds, increasingly, the adaptation literature emphasizes the social dimensions of adaptation limits [2,26,31,32]. This concept of adaptation limits therefore provides a social context that complements that which focuses on biophysical boundaries toward a more integrated view of socio-ecological limits to sustainability. Elements of the Earth system can be pushed into socio-ecological spaces, where values and objectives are potentially unsustainable.

The prospects for sustainability are influenced, however, by the adaptive responses of society, which are finite.

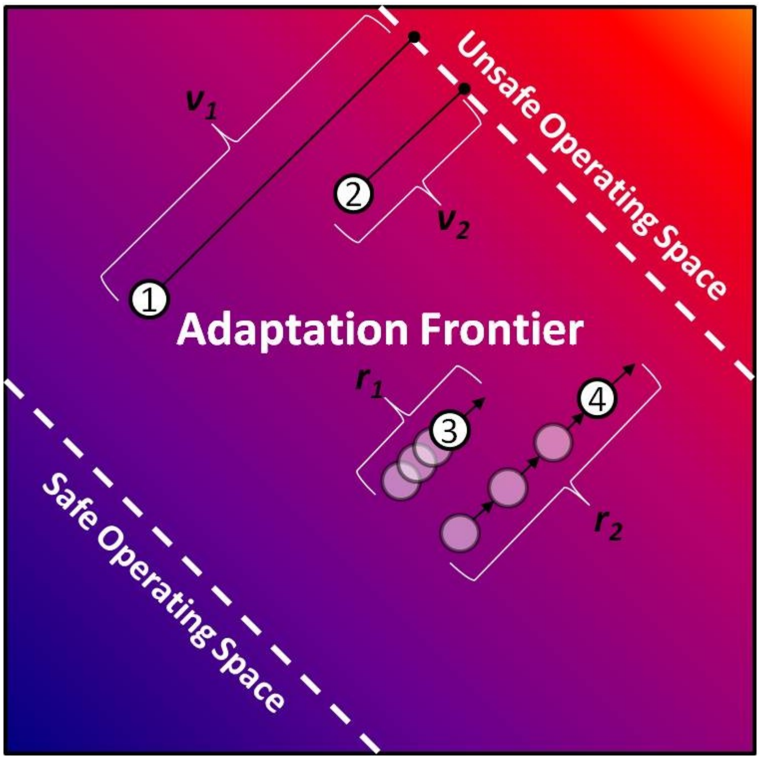
The adaptation frontier, therefore, represents the domain between a socio-ecological system's safe operating space and its unsafe operating space, where multiple factors threaten to erode a system's sustainability, but where adaptation still has the potential to secure the management objectives and values ascribed to that system by human actors. It represents a frontier in the sense that, while adaptation options are available in principle, it is unclear whether or not such adaptation will in fact be deployed with sufficient efficacy and timeliness in practice to realize sustainable outcomes. Hence, the prospects for sustainability on the adaptation frontier are ambiguous and contingent upon future developments, not the least of which is human choices regarding investments in adaptation. The edge of the frontier effectively represents the limits of adaptation, beyond which objectives and values can no longer be maintained through adaptation [26].

The boundaries of the adaptation frontier for a given system are difficult to define due to uncertainty regarding the capacity of systems to adapt to changes in climate, as well as the complex interactions among driving forces that influence where a system is positioned with respect to the frontier. As such, the adaptation frontier is best conceptualized not as a discrete and static threshold, but rather an uncertainty or probability space characterized by a gradient that reflects an increasing likelihood of crossing into an unsafe operating space (Figure 1). That probability space is influenced by the pressures on a system of interest, as well as the effectiveness of its adaptive response.

Adaptation can therefore offer two types of benefits to systems on the frontier. First, systems can be managed so as to reduce their vulnerability, effectively moving them away from the edge of the frontier and expanding the range of options available for securing a safe operating space. Second, adaptation can enhance resilience, enabling systems to persist despite the continued presence of and exposure to pressures. In this context, the ultimate success or failure of climate adaptation lies in its ability to keep systems from falling off the edge of frontier boundaries, despite multiple driving forces.

While integrating multiple concepts found in the literature, the concept of an adaptation frontier is aligned with adaptation theory. A system's position *vis-à-vis* the frontier is influenced by two factors. First, the distance of a system from the edge of the frontier represents its vulnerability ($v$). Those systems that remain distant from the edge of the frontier ($v_1$) have more options and resources to adapt and more time to anticipate adaptation needs and implement interventions. In contrast, those systems already precariously positioned at the edge of the frontier ($v_2$) have few additional mechanisms for adapting and, thus, are most in danger of crossing the edge into an unsafe operating space. For example, montane, boreal forest and coral reef ecosystems all persist at the edge of their climatological limits and, thus, have little capacity to adapt to climatic change [33–36]. Similarly, poverty has been identified as a key factor influencing the vulnerability of human populations to climate variability and change [37,38]. Second, the rate ($r$) at which a system is pushed toward the edge of the frontier is a function of its resilience (Figure 1). Hence, some systems ($r_1$) are more resilient to driving forces than others ($r_2$) and, thus, have a greater chance of actively maintaining stability under stress [19,39,40], thereby avoiding an unsafe operating space. These two properties of vulnerability and resilience obviously interact. For example, systems with low resilience become increasingly vulnerable to climate and/or other stressors as they are pushed closer to the edge of the frontier.

**Figure 1**. A conceptual map of the Adaptation Frontier. The frontier lies between a system's safe and unsafe operating space. Different systems (1–4) are positioned and behave heterogeneously within the frontier. Systems 1 and 2 demonstrate systems with different distances from the edge of the unsafe operating space, with system 1 having less vulnerability than system 2, due to its greater distance. Systems 3 and 4 are moving more or less rapidly toward the edge of the frontier, with system 3 having greater resilience than system 4, due to a lower rate of migration.




## 3. Beyond the Frontier—The Earth System's "Manifest Destiny"?

Much of the surge in interest in adaptation can be attributed to a complex suite of biophysical, socioeconomic and political factors, all of which imply an increasing urgency with respect to managing climate risk. The biophysical factors include increasing evidence of an anthropogenic signal in recent climate trends and extreme climatic events [41,42], as well as a likely commitment to exceeding estimated thresholds for "dangerous anthropogenic interference" (e.g., a 2.0 °C increase in global mean temperature) [43–48]. The socioeconomic factors include growing awareness of the vulnerability of socioeconomic systems to climate variability and change [19,20], as well as demographic change and economic development that increase the interconnectedness of those systems and their exposure to climate [49–53]. Meanwhile, the political factors include a backlash against international and national failures to secure substantive agreements to reduce greenhouse gas emissions, as well as demands by developing nations for assistance in reducing the consequences of climate change. While these myriad challenges are discussed extensively in the literature [1,2,19,20], here, it's argued that a relatively small number of driving forces appear to be playing a key role in determining the fate of systems on the adaptation frontier by posing critical challenges to their sustainability (Table 1).

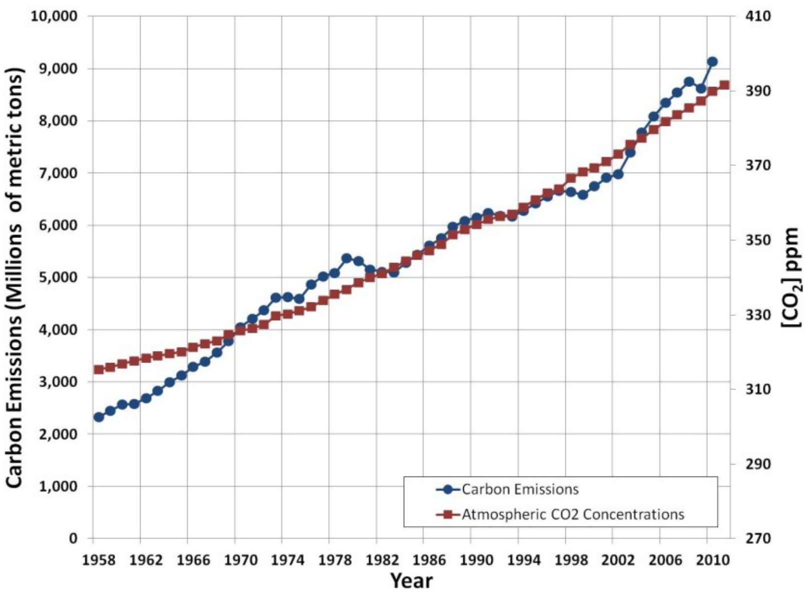
**Table 1.** Summary of the symptoms and implications of key driving forces influencing the position of socio-ecological systems on the adaptation frontier.

| Driving Force | Symptoms | Implications |
|---|---|---|
| **Adaptation/development deficits** | • Persistent vulnerability to climate variability<br>• Engagement in unsustainable activities and enterprises<br>• Depreciation of existing assets and infrastructure | • Impairment of ecological systems<br>• Underperformance and reduced resilience of societal assets |
| **Path dependence** | • Continued growth in greenhouse gas emissions<br>• Increasing population growth and economic development | • Increased likelihood of climate changes beyond the limits of adaptation<br>• Increasing exposure of human populations to climate extremes and damages<br>• Increasing pressure on ecological systems |
| **Uncertainty in limits** | • Lack of confidence regarding where limits lie<br>• Reliance upon assumption and heuristics to guide understanding of adaptation limits<br>• Governance/institutional complexity | • Over or underestimation of adaptation limits<br>• Reduced perception of the need to avoid limits<br>• Increased risk of crossing limits inadvertently<br>• Reduced capacity of actors to anticipate or respond to opportunities and barriers to adaptation |
| **Competing values** | • Inconsistent policy agendas with respect to mitigation and adaptation polices and measures<br>• Lack of public support or demand for adaptation and mitigation policies and measures | • Focus on near-term benefits of adaptation policies and measures<br>• Enhanced difficulty in pursuing actions that would ensure limits are avoided |
| **Discounting of future loss and damage** | • Informal discounting of climate change consequences by society<br>• Formal discounting of future loss and damage in investment planning<br>• Reliance upon traditional policy analysis tools as means of evaluating mitigation and adaptation policies and measures | • Reduced perception of the urgency of adaptation<br>• Increased constraints on opportunities for enhancing resilience<br>• Persistent bias toward maintaining economic values over social, cultural or environmental values |

### *3.1. Path Dependence*

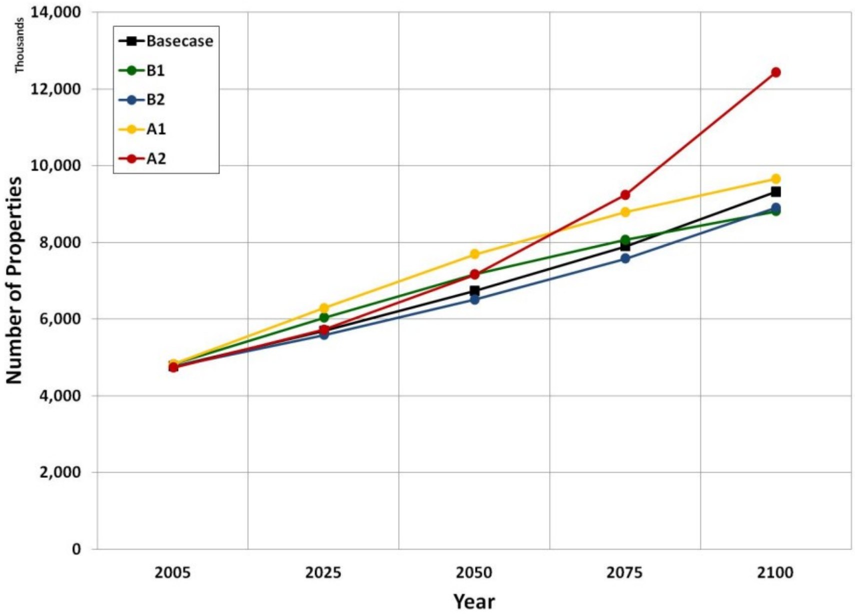
One of the critical factors influencing the rate at which systems advance toward their frontiers is path dependence, meaning that past decisions regarding economic development, technology, as well as social norms and behaviors constrain the extent to which systems can adapt to the changing climate. Although the issue of path dependence and adaptation appears in the literature [54–56], it has largely been discussed in the context of the global warming commitment. At global scales, the trajectory of emissions and atmospheric greenhouse concentrations demonstrates strong growth despite the current concerns regarding climate change and international agreements, such as the UNFCCC. For example, data from the Carbon Dioxide Information Analysis Center through 2010 illustrates steady increases in fossil fuel carbon emissions, as well as carbon dioxide in the atmosphere (Figure 2), despite the impacts of the global financial crisis on global economic development. Growth in global energy demand when combined with existing capital investments and technologies contribute to significant inertia in the structure of the global energy system and its associated emissions. This path dependence is evidenced by both the Special Report on Emissions Scenarios and the more recent Representative Concentration Pathways that indicate future emissions and/or radiative forcing will increase over at least the next half century [57,58]. The inertia of greenhouse gas emissions and concentrations contributes to inertia with respect to changes in climate. This concept of "committed warming" and its magnitude relative to estimated thresholds for "dangerous anthropogenic interference" (e.g., a 2.0 °C increase in global mean temperature) have become a central element of climate policy, including both mitigation and adaptation.

**Figure 2.** Global carbon emissions and atmospheric carbon dioxide ($CO_2$) concentrations (1958–2010). Data were obtained from the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory [59–61].




Path dependence extends beyond physical systems. Accordingly, "committed warming" should be considered within a larger context of "committed vulnerability", whereby the inertia of both climatic and socioeconomic systems will interact to commit communities to future increases in adverse consequences [53]. For example, societal vulnerability to climate change—past, present and future—is influenced by the degree of exposure to climatic extremes and natural hazards [49–53,62–65]. While future economic development is likely to enhance some determinants of adaptive capacity of communities and industries [66,67], the associated growth in wealth combined with future population growth will increase socioeconomic exposure to climate variability and change. Observed global and US trends toward rising economic losses associated with climatic extremes [68,69] suggest that the assumed high adaptive capacity of developed nations, such as the United States, may not be sufficient to offset growth in at least the direct economic losses of future extremes. Meanwhile, examination of scenarios of future socioeconomic conditions indicate continued population growth and development are likely to place more and more people in harm's way. For example, US projections of growth in housing in coastal flood plains indicate exposed housing will increase by 40–50% by 2050 and 100–150% by 2100 (Figure 3). For ecological systems, impaired aquatic habitat, overexploitation of fisheries, widespread land use change and the global extinction crises have all contributed stocks of natural capital being less today than they have been in the past [70,71]. In addition, these outcomes are indicative of systems that are under persistent pressure from non-climatic threats. Enabling such systems to adapt naturally to the effects of climate change may therefore require them to first stabilize in the current climate by reducing such pressures. Achieving this goal, however, would require addressing the various socioeconomic trends that are responsible for putting pressure on ecological systems.

**Figure 3.** Projections of growth in the number of US housing units occurring in coastal and estuarine Special Flood Hazard Areas as defined by the US Federal Emergency Management Agency [72]. Projections are based upon the Integrated Climate and Land Use (ICLUS) 1 hectare gridded housing density scenarios [73], which were developed to be consistent with the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios [57]. ICLUS data were extracted for Special Flood Hazard Areas (SFHAs) using Geographic Information Systems and aggregated to generate national statistics.



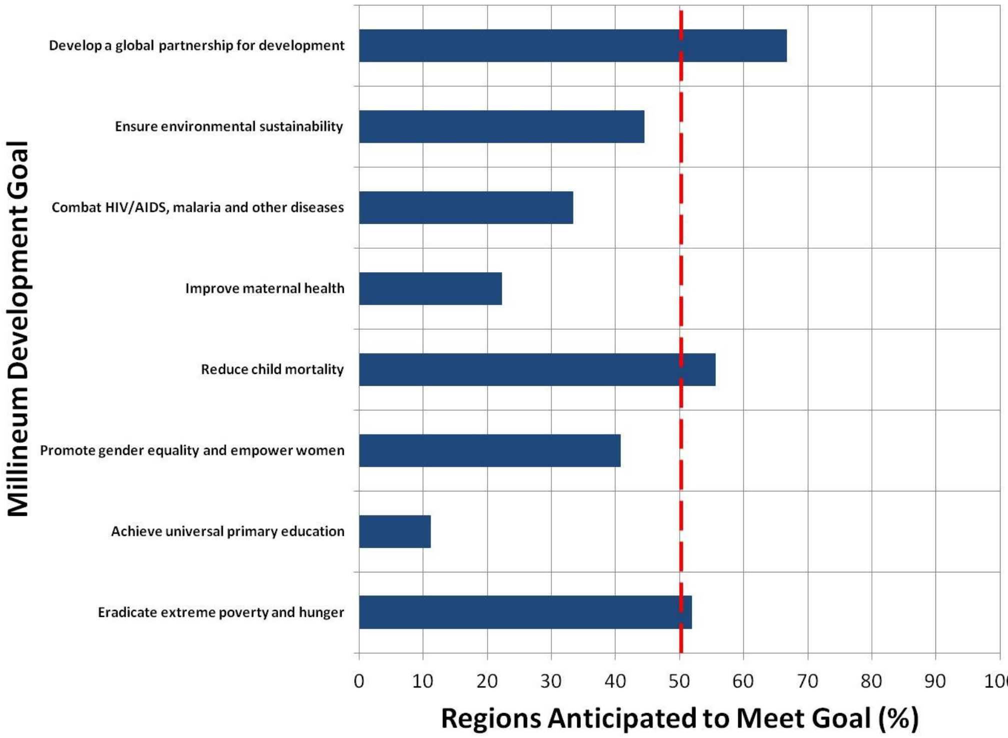
### *3.2. Adaptation and Development Deficits*

While path dependence largely influences the rate at which climate change drives systems toward the edge of the adaptation frontier, many systems already persist at their limits of adaptation and, thus, are particularly vulnerable to the effects of climate change. Hence, key considerations with respect to the adaptation frontier are adaptation and development deficits. The concept of an adaptation deficit refers to systems that are poorly adapted to the climate that system currently experiences [1,74–78]. The related concept of a development deficit refers to a condition in which a system's capacity to adapt to the effects of climate change is constrained by underdevelopment [79]. The distinction between the two rests on the capacity of actors—adaptation deficits suggest capacity may exist, but has yet to be effectively deployed, whereas development deficits suggest the presence of more fundamental constraints on capacity.

A leading cause of adaptation deficits is a failure to adequately invest and/or maintain investment in those assets and practices that promote system resilience. For example, at a minimum, the current US adaptation deficit is US$2 trillion, which is the estimated cost to address the depreciation of existing US infrastructure [80]. This implies that the current stock of infrastructure is underperforming and, thus, has a greater degree of vulnerability to climate variability than it would if investments had been made to avoid the deficit. This deficit also suggests that investments in adaptation will compete with investments made to address existing needs with respect to infrastructure maintenance. Meanwhile, demands for new infrastructure will continue to rise due to population growth and economic development. Another dimension to the adaptation deficit is the existence of management practices that have or will prove to be maladaptive given climate variability or future climate change. Such maladaptive actions may fail to achieve desired objectives and/or conflict with the values and objectives of other actors [81]. Efforts and investment that could have been allocated to adapting to future climate change must be siphoned off for remedial actions to address systems that are dysfunctional. Hence, the legacy of past socioeconomic development combined with the failure to invest in maintaining and improving that development has already generated a large, yet unmet, demand for adaptation. Those unmet needs, unless reconciled, reduce system resilience, increase vulnerability and, therefore, increase the likelihood of exceeding adaptation limits.

A more profound challenge, however, is development deficits, where investments of resources specifically for climate adaptation are insufficient to ensure systems can be managed in sustainable ways due to underlying development challenges. Such development deficits are perhaps most evident in the face of extreme events and natural disasters, which, in developing nations, continue to take a heavy toll in terms of human mortality, displacement and economic disruption [20]. Despite ongoing international efforts to eliminate poverty and other symptoms of underdevelopment, as evidenced by progress toward the UN's Millennium Development Goals (Figure 4) [82], challenges to human security and well-being persist. The constraints on the capacity of developing nations to collectively address such challenges means that the limits to adaptation in developing nations are more profound than in the developed world, and thus, the edge of the adaptation frontier is much closer relative to comparable systems in developed nations [1].

**Figure 4.** Reported progress toward achievement of the United Nations Millennium Development Goals (MGDs). Data are based on a 2012 assessment of selected key targets relating to each of the eight MGDs [82]. Progress against targets was reported for nine global regions. Percentages represent the proportion of regions on track to meet the specified targets for each MGD.




*3.3. Uncertainty in Limits to Adaptation*

While it is possible to brainstorm about a broad range of climate changes that would challenge adaptation efforts, understanding where such limits lie in practice is an area of ongoing research. Investigators have posited that biophysical feedbacks due to climate change could lead to tipping points in the Earth system [29,30,83], some of which would pose significant challenges to natural ecosystems and human-managed systems. For example, collapse of the Greenland ice sheet, loss of the Amazon rain forest, large-scale bleaching of coral reef ecosystems or loss of rice cultivation in tropical regions would all have significant downstream implications for natural ecosystems and human populations [33–36,83–85]. Yet, understanding of such tipping points and thresholds remains poor. In ecosystem science, substantial questions remain regarding the significance, identification and interpretation of thresholds [86,87] Similarly, specifying species- and location-specific climate thresholds that represent limits to adaptation remains challenging, as does assessing the likelihood of exceeding such thresholds [88–90]. However, limits to adaptation are influenced not just by biophysical processes, such as climate change, but also by social processes and the values of individual actors [2,26,31,32]. For instance, maintaining current yields of some perennial crops in California may require shifting production locations, although topography, soils, competing land uses and irrigation infrastructure may limit feasibility [91]. Hence, the determination of an adaptation limit is highly contingent upon uncertainties regarding adaptation options, their implementation and their effectiveness.

Yet, little effort has been invested to date in addressing such uncertainties, and understanding of social systems has been poorly integrated into conceptualizations of socio-ecological thresholds [92,93].

In addition to fundamental uncertainty regarding thresholds and tipping points in socio-ecological systems, additional uncertainty arises from scale dynamics and their implications for limits to adaptation. Adger *et al.* [2] note that the management of climate risk through adaptation invariably involves multiple scales of governance. This complexity imposes barriers on the planning and implementation of adaptation, as each scale must work in harmony with the others for effective adaptation to be realized. Achieving such harmonization is challenging, but more importantly, success in this regard is difficult to predict. Recent actions by State governments in both the US and Australia illustrate this. In 2012, for example, the US State of North Carolina passed legislation barring consideration for future sea-level rise greater than historical trends in assessing risks to coastal development [94]. At the same time, the Australian State of New South Wales amended its Coastal Protection Act 1979 [95], rescinding reforms introduced in 2009 to encourage greater consideration for the risk of sea-level rise to properties and promote planned retreat over protection measures for private property. Such cases also illustrate how policy uncertainty can undermine adaptation efforts and how actor objectives, as well as the limits to adaptation, vary across scales of governance [96]. This raises equity issues with respect to where investments and interventions are targeted to enhance adaptive capacity and avoid limits. The goals of adaptation can be narrowly framed so as to protect the near-term interests of a select few or more broadly framed to attempt to sustain the interests of society-at-large over the long-term. Adaptation science is poorly equipped at present to resolve such complexities (or even identify who should undertake the resolution), leaving actors to muddle along the adaptation frontier unsure of what outcomes will ultimately be realized.

### *3.4. Competing Values*

The objectives of society, including the objectives sought through climate adaptation, are ultimately a function of societal values [26,70,97]. Globally, those values have consistently been closely aligned with the principles of sustainability, at least at a political level. The UNFCCC, for example, specifies the goal of international climate policy as the prevention of "dangerous" climate change. Meanwhile, there is international agreement over the UN's Millennium Development Goals [98], the Universal Declaration of Human Rights [99] and the Convention on Biological Diversity [100]. Such political agreements, however, don't necessarily ensure positive outcomes are realized in practice [101]. The international community is not on track to achieve the MGDs, the degradation of biodiversity continues at global to local scales and securing human rights remains challenging in many nations. Making progress in securing such values is constrained when there is competition among values, which force trade-offs in the allocation of finite human, financial and political capital to address societal challenges.

The adaptation frontier is where conflicts among values are particularly acute and where tradeoffs will have to be made. The sustainability of systems is threatened, creating demand for adaptation interventions. Yet, the uncertainty regarding the limits of adaptation, combined with societal imperatives to achieve other objectives, can place adaptation in opposition to other policy goals. Hence, investments in climate adaptation, particularly over the near-term, may be perceived as an opportunity cost [102]. Such trade-offs may result in some actions being simultaneously perceived as adaptive and maladaptive [103], depending on the perspective of stakeholders. O'Brien [31] and O'Brien and Wolf [32] argue that values ultimately limit the ability of actors to plan and implement effective responses to climate change. For example, at local scales, Measham *et al.* [14] report that some local government stakeholders in Australia find it difficult to elevate adaptation on the policy agenda, given other responsibilities and the absence of a legislative mandate. Thomsen *et al.* [104] also suggest that values influence how actors approach adaptation, with the majority of adaptive responses representing manipulations of actors' socio-ecological contexts to achieve short-term fixes, as opposed to long-term and sustainable adaptation. Meanwhile, identity and ideology influence one's perspective on the reality and/or significance of climate change [1] and, subsequently, one's willingness to engage in the evaluation of climate risks and the planning and implementation of adaptation.

### *3.5. Discounting the Costs and Benefits of Adaptation*

A specific mechanism by which values manifest that has particular bearing on the limits of adaptation to manage climate change risk is the tendency to discount the future costs and benefits of climate change impacts, as well as adaptation and mitigation options [105–110]. This discounting occurs implicitly and informally as one contemplates priorities for the allocation of resources and associated tradeoffs, with evidence suggesting individuals' discounting of the future varies over different time scales. The cognitive aspects of discounting appear to be somewhat hard-wired into human neurophysiology [111–115] and, therefore, are an intrinsic feature of daily decision-making. In some ways, such cognitive tendencies are adaptive in that they focus decision-making around the resolution of immediate needs and maximization of near-term gains relative to longer-term and less certain outcomes. At the same time, however, such discounting reduces the perceived urgency associated with future risks relative to current risks, and therefore, it increases the likelihood that adaptation decision-making will be driven by the near-term costs of implementation, as opposed to long-term benefits. Furthermore, discounting is also applied explicitly and formally in the quantification of the cost effectiveness of different climate risk management strategies to inform policy [109,110]. As a case-in-point, the construction of a desalination plant in Victoria, Australia, to ensure water supply security to metropolitan Melbourne has been labeled maladaptive due to doubts regarding its necessity and long-term cost-effectiveness [81,116].

In terms of informing policy, the application of a given discount rate is less of an inherent feature of cognition and more of a normative decision—one, which has ethical implications. Particularly with respect to the pure rate of time preference, the selected rate effectively represents the extent to which the welfare, values and needs of future generations will be discounted, simply because they occur in the future. This is ultimately a choice about the extent to which current generations will discriminate against future generations [109]. Hence, the choice of which discount rate to use in climate change policy analysis has been a matter of intense debate [109,110], as has the appropriateness of cost/benefit analysis in general [117–119]. Nevertheless, while such debates will continue in academic discussions of the cost and benefits of climate policy, on a more practical level, investments in specific adaptation options, such as infrastructure, are ultimately financial transactions implemented by individual actors, the costs and benefits of which are likely to be evaluated using some non-zero discount rate. The US government, for example, applies a 7% discount rate in cost/benefit analysis of US federal policies and investments [120]. Hence, adaptation investment decisions are likely to continue to be governed by standard business practices with respect to discounting. Leaving aside the appropriateness of this, adapting to some impacts will invariably be perceived as prohibitively expensive [79], particularly in the absence of greenhouse gas mitigation, suggesting some societal values and objectives will be forfeited, resulting in loss and damage (see Section 4). This is exacerbated by the fact that estimates of the costs and benefits of climate policy largely neglect non-market values. For example, the Stern Review on the economics of climate change acknowledged that the estimated impacts of climate change would be higher if non-market costs were considered, but such costs were excluded from the analysis [110,119]. Thus, some consequences are likely to simply be excluded from the calculus of the efficacy and efficiency of adaptation, and thus, those consequences are likely to go unmanaged.

## 4. Life on the Frontier

The key driving forces identified in Section 3 suggest that socio-ecological systems at the frontiers of adaptation will likely be plagued by increasing, but uncertain, threats to sustainability and, as a consequence, increasingly intensive deliberation and conflict regarding investments in adaptation responses in order to maintain objectives and values. This deliberation will likely extend well-beyond "no regrets" options into debate over fundamental trade-offs in societal values. Meanwhile, systems currently persisting at their adaptation limits will likely venture beyond the frontier into uncharted, unsafe and unsustainable domains. However, according to Adger *et al.* [2], "limits to adaptation are mutable, subjective and socially constructed", reflecting the role of human agency in influencing when and if limits to adaptation are exceeded [26]. For example, much of adaptation theory is predicated on the belief that increasing the availability of and entitlements to capital resources (finance, technology, *etc.*) will enhance the capacity of actors to adapt, thereby expanding the range of climate change, which can be managed before limits are reached. Such enhanced adaptive capacity may expand the coping capacity of a system, thereby increasing its resilience to stress or open up additional adaptation options that expand the edges of the frontier, thereby reducing the vulnerability of a system within the frontier. Nevertheless, none of the aforementioned threats to sustainability are readily ameliorated, and thus, society is unlikely to forestall all loss and damage arising from climate change.

Some systems may find themselves transitioning in and out of unsafe operating spaces in response to the dynamics of the adaption frontier. For example, dryland cropping systems in South Australia have long been demarcated by Goyder's line—the climatological limit between sustainable and unsustainable cropping [121]. Though originally developed as an agro-ecological isocline, history has shown that the line migrates along a north-south gradient, and thus, cropping has at various times moved north of Goyder's line for extended periods of time during favorable conditions before ultimately retreating southward as conditions deteriorate [122]. Goyder's line, therefore, represents a tangible, practical analogy to the probabilistic adaptation frontier. It also illustrates how life on the frontier can be associated with transient successes and failures, with systems moving in and out of unsafe operating spaces, as the biophysical and socioeconomic determinants of vulnerability and resilience change over time. This is consistent with theories of adaptation based on adaptation cycles or social learning loops, characterized by periods of incremental adjustments, followed by transformational events, as the context of actors and systems change [96,123,124].

Perhaps one of the most neglected considerations with respect to limits to adaptation is what happens once a limit is reached. Two potential outcomes seem plausible [26]. First, actors can proactively change their management or adaptation objective, thereby placing themselves on a different adaptation pathway. Hence, those systems that are in danger of crossing over the edge of the frontier can be transformed to greatly reduce vulnerability, enhance resilience and enable sustainability. For example, Park *et al.* [96] observe that Australian wine producers are exploring opportunities to expand viticulture into new regions and, therefore, are establishing new management objectives where managing risk in place is accompanied by exploiting opportunities elsewhere. Such behavior is inherently adaptive and even transformative, despite an adaptation limit being reached. Transformational adaptation of systems in anticipation of adaptation limits may be an effective adaptation pathway to achieving higher order societal objectives [26,96,125–127], even if that means some proximal objectives are no longer sustainable [2]. Transformation, therefore, provides an adaptive mechanism for addressing the challenges created by path dependence, values conflicts and social discounting. Second, and more destructively, reaching a limit can result in loss and damage [26,128–130]. This, too, may ultimately result in actors dependent upon such systems to reactively revaluate objectives, if for no other reason than prior objectives are no longer obtainable. Hence, encountering a limit appears to trigger some form of transformational change—either with respect to how a system is managed and/or in the sustainability of the system itself. The key tension appears to be whether actors choose to transform or have transformation forced upon them.

## 5. Discussion

The adaptation frontier is a space where both risk and opportunity coexist, with human agency acting as the arbitrator of outcomes. In fact, the frontier is in itself a product of human design, with societal choices regarding greenhouse gas emissions, socioeconomic trajectories and social values interacting to both threaten the sustainability of socio-ecological systems, as well as craft adaptive solutions to maintain a safe operating space. While presented here as largely a conceptual construct, the adaptation frontier focuses the framing of adaptation around the most policy relevant questions, as the sensitivity of the fate of socio-ecological systems to human decisions regarding adaptation planning and implementation is greatest at the frontiers of adaptation. Those systems for which there is high confidence regarding their future sustainability may encounter few critical decision points or trade-offs. Meanwhile, those for which adaptation limits have already been exceeded can no longer be aided by adaptation. Hence, the domain between these two extremes is where adaptation decision challenges are most acute and where human agency has the greatest bearing on socio-ecological outcomes.

It is important, however to reflect, upon the utility of the concept of the adaptation frontier relative to the existing discourse regarding biophysical planetary boundaries and socially-constructed limits to adaptation. In this respect, the concept of a frontier embodies three elements that may be important to the framing of adaptation in both research and practice:

(1) *Integration*: The adaptation frontier recognizes that there are limits to the pressures that socio-ecological systems can endure before they can no longer sustain societal values and

objectives. However, rather than these limits being simply a function of discrete climatic thresholds, they are emergent properties of multiple determinants. Some of these determinants are biophysical, but others originate solely within socioeconomic systems.

(2) *Ambiguity*: The limits to the sustainability of socio-ecological systems cannot be clearly demarcated, as they are contingent upon human values and choices that have yet to be made. Uncertainty regarding these aspects of the adaptation frontier is irreducible, and thus, the frontier domain and its boundaries are unavoidably ambiguous. A meaningful discussion regarding the capacity of adaptation to provide sustainable outcomes, therefore, requires some *a priori* assumption or articulation of sustainability objectives, as well as a holistic accounting of the pressures experienced by systems and the mechanisms by which those pressures can be managed.

(3) *Transformation*: The concept of an adaptation frontier shifts the discourse around adaptation from one focused on incremental adjustments that yield incremental benefits to one focused on system transformation. The existence of limits to sustainability, even with investments in adaptation, suggests that loss and damage is a likely consequence of climatic and non-climate change. While some degree of loss and damage may be borne by some systems, for others they may pose a fundamental threat to sustainability objectives. Hence, adaptive transformation that fundamentally alters actors' perspectives on sustainability, societal objectives and how they can be achieved may be necessary to secure a safe operating space.

These elements suggest that complexity, ambiguity and uncertainty are common, cross-cutting features of the adaptation frontier; ones that pose challenges to conventional risk analysis, policy analysis and management methods. While there is a clear need to enhance understanding regarding the response of systems to climate change, as well as the opportunities that exist for adaptation and their limits, doing so will require leveraging more than scientific/technical knowledge in decision-making. Many forms of adaptation will be contested, necessitating mechanisms to reconcile conflicting values if effective adaptation planning and implementation is to proceed. The extensive literatures of risk governance, adaptive governance and policy sciences provide guidance for how to approach such decision challenges [131–139]. A common feature of such approaches to problem solving is active participation by civil society in sharing and shaping knowledge regarding societal objectives, perceptions and tolerance of risk to those objectives and appropriate responses by different actors. Nevertheless, these principles have yet to be mainstreamed into practical decision-making regarding climate risk management and adaptation. Therefore, while adaptation efforts will understandably focus on those actions that can be implemented within the limits of human agency and adaptive capacity, mechanisms—such as adaptive transformation or compensation for loss and damage—must also be developed for addressing those failures of sustainability that cannot or will not be avoided.

Ultimately, successful navigation of the adaptation frontier will likely be dependent upon the evolution of how society values the potential consequences of climate change and available options for their amelioration. History has witnessed systems being pushed to the edge of collapse only to be rescued and returned to a sustainable sate, and such discrete successes stand out against a background of chronic degradation of others. Stark challenges for human development and security persist despite decades of investment. Land use change and the loss of ecosystem services continue to contribute to the current extinction crises. The consequences of underinvestment in infrastructure that conveys resilience and human capital that promotes innovation are becoming increasingly apparent, particularly in the relatively wealthy nations of the developed world. Therefore, two types of changes in values seem necessary. The first is to more effectively deploy policies and measures that can achieve the aspirational goals embodied by international agreements, such as the UNFCCC, the CBD and the MGDs across scales. At the same time, however, the assumption that socio-ecological systems can, or even should, continue to be managed based upon traditional objectives needs critical reevaluation. Increasingly intensive manipulation of environmental systems to meet management objectives may not be a robust pathway to long-term sustainability [102]. Eventually, options for such manipulation may be exhausted, and the externalities of that manipulation may undermine the objectives that actors are attempting to maintain.

## 6. Conclusions

The sustainability of socio-ecological systems across a range of scales may be threatened by climate change, particularly given persistent challenges in realizing substantive reductions in anthropogenic greenhouse gas emissions. While there are significant opportunities for adaptation to assist in achieving sustainable outcomes despite the changing climate, those opportunities are finite. The climate change research community has endeavored to elucidate potential climate "tipping points" and thresholds as a means informing decision-making around climate risk management. However, such reductionist approaches to risk management overlook the complexity and uncertainty associated with socio-ecological systems and, in particular, the role of human agency in determining whether or not the limits to adaptation are experienced. Therefore, the adaptation frontier remains largely unexplored, and this ignorance complicates the adaptation challenge. There is a clear need for more rigorous exploration of the frontiers of adaptation to better inform understanding of adaptation opportunities, as well as identify likely sources of loss and damage. Engaging in this effort, however, will require an integrated approach to risk governance that embraces both the normative and analytic elements associated with risks to sustainability and the ethical implications of different decision alternatives [26]. Nevertheless, even if substantive progress were to be made in this regard, systems on the adaptation frontier are likely to be fundamentally changed, with a critical uncertainty being whether such changes are ultimately perceived as being positive or negative.

## Acknowledgments

The lead author's contributions to this research were sponsored through Oak Ridge National Laboratory's (ORNL) Laboratory Directed Research and Development Program. ORNL is managed by UT-Battelle, LLC, for the US Department of Energy under contract DE-AC05-00OR22725. The author acknowledges the assistance of Megan Maloney in the analysis of some of the data sources reported in this paper, as well as conversations with Mozaharul Alam, Richard Klein, Guy Midgley and Rebecca Shaw that informed this paper's discussion of limits to adaptation.

**Conflict of Interest**

The authors declare no conflicts of interest.

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